INDUCTION MOTOR PERFORMANCE TESTING WITH AN INVERTER POWER SUPPLY, PART 2

By:

R.C. Zowarka
T.J. Hotz
J.R. Uglum
H.E. Jordan

13th Electromagnetic Launch Technology Symposium, Potsdam (Berlin), Germany, May 22-25, 2006

IEEE Transactions on Magnetics, vol. 43, no. 1, January 2007, pp. 275-278

PR 427

Center for Electromechanics
The University of Texas at Austin
PRC, Mail Code R7000
Austin, TX 78712
(512) 471-4496

Induction Motor Performance Testing With an Inverter Power Supply: Part 2

Raymond C. Zowarka, Thomas J. Hotz, John R. Uglum, and Howard E. Jordan
The University of Texas at Austin – Center for Electromechanics

Abstract -- The development of high power density electrical machines continues to accelerate, driven by military, transportation, and industrial needs to achieve more power in a smaller package. Higher speed electrical machines are a recognized path toward achieving higher power densities.

Existing industry testing standards describe well-defined procedures for characterizing both synchronous and induction machines. However, these procedures are applicable primarily to fixed frequency (usually 60 or 50 Hz) power supplies. As machine speeds increase well beyond the 3,600 rpm limitation of 60 Hz machines, a need for performance testing at higher frequencies is emerging.

An inverter power supply was used to conduct a complete series of tests on two induction motors (0.5 MW and 1.0 MW) with speeds up to ~ 5,000 rpm. The use of a non-sinusoidal power supply with limited power output capability required the development of measurement techniques and testing strategies quite different than those typically used for 60/50 Hz testing.

Instrumentation and techniques for measuring voltage, current and power on harmonic rich waveforms with accuracies approaching 1% are described. Locked-rotor and breakdown torque tests typically require large kVA input to the motor, much higher than the rated load requirement. An inverter sized for the rated load requirements of the motor was adapted to perform locked-rotor and breakdown torque tests. Inverter drive protection features such as anti-hunting and current limit that were built into the inverter had to be factored into the test planning and implementation.

Test results are presented in two companion papers. Part 1 correlates test results with the results of an algorithmic induction motor analysis program. Part 2 (this paper) presents the test results compared with a Matlab™ simulation program and also provides a comprehensive discussion of the instrumentation that was essential to achieve testing accuracy.

I. INTRODUCTION

Testing practices for synchronous and induction machines have been developed over the years and documented in detail in IEEE Standards [1,2]. Since the vast majority of electrical machines are applied at electrical power frequencies, it is to be expected that the testing procedures are based on a fixed frequency power supply, usually 50 or 60 Hz. An increasing number of induction motors are now being designed to operate from inverters and, therefore, are not constrained to 50 or 60 Hz power. Testing at 50 or 60 Hz does not provide the performance information needed for the inverter-powered motors operating at higher frequencies.

An inverter rated to power the induction motors being tested was used as the power supply for a complete series of tests which included:

- No-load saturation
- Locked-rotor saturation
- Breakdown torque
- Load performance
- Temperature test

II. TEST RESULTS COMPARED TO SIMULATION

In designing the motor characterization procedure using a pulse width modulated (PWM) drive, a commercial motor with known parameters was tested first. As part of that testing, a simulation of the system was developed using Matlab™. The comparison of experiment to simulation is presented in this section of the paper. The overall experimental setup is shown in Fig. 1.

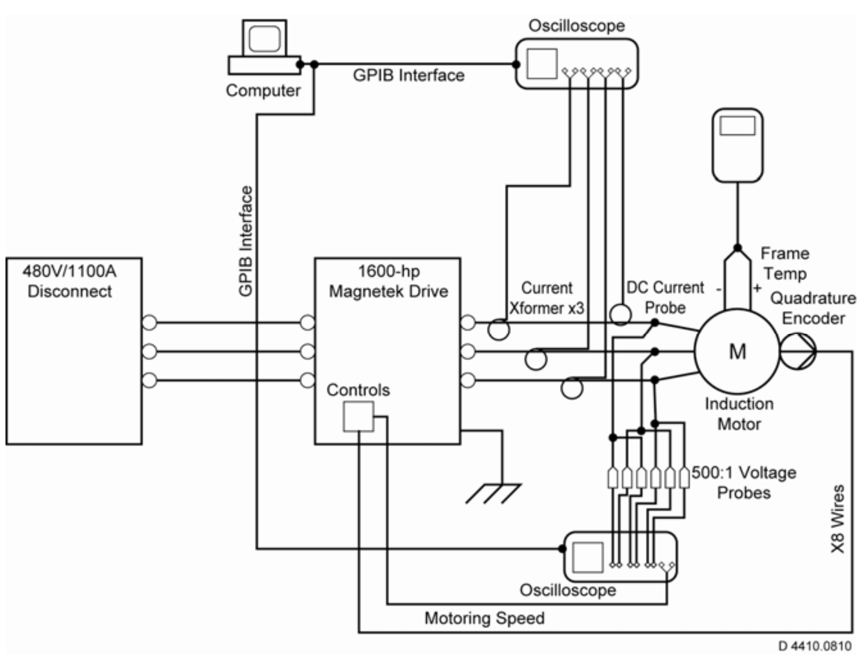

Fig. 1. Instrumentation diagram for testing 500 hp Toshiba motor

The inverter drive is a Magnetek model GPD515 1,600 hp motor drive. The induction motor is a 500 hp Toshiba model 3F4500L3C9632 motor.

The nameplate data for the Magnetek motor drive is:

Model #:	G5U-5C00
S/N:	223319-1687
hp/kVA:	1,600
FLA:	1,600
Input volts:	600
Phases:	3
Hertz:	60
Fault kA:	10
Input amps:	1,800

In simulation, a three-phase PWM voltage source inverter with unipolar voltage switching logic was used to model the Magnetek motor drive [3]. The motor is rated at 500 hp, 3,580 rpm, 460 V, and 60 Hz. The induction motor was modeled with the Matlab™ SimPowerSystems software asynchronous machine in the dq rotor reference frame. This software contains several motor modeling packages. The asynchronous machine in the dq rotor reference frame [4] was used here. Nameplate information of importance for the simulation is given in Table 1.

The first test simulated was the no-load test. Figs. 2 and 3 demonstrate that the long term behavior of the simulation results match the experimental data. Figs. 4 and 5 expand the detail of the PWM and once again demonstrate a good match of simulation to experiment. The second series of tests simulated were the locked-rotor tests. Figs. 6 and 7 show that the long term behavior of the simulation matches experiment with no offset or drift. Figs. 8 and 9 demonstrate that the detailed switching of the PWM was captured well in simulation. For the locked rotor test a torque of 186 ft-lb was measured in the experiment. The simulation predicted a torque of 178 ft-lb.

TABLE 1. TOSHIBA MOTOR SIMULATION INPUT DATA

Parameter and units	Value
Nominal power (VA)	436,000
Voltage line-line (V)	460
Frequency (Hz)	60
Stator resistance (ohm)	0.00306
Stator inductance (H)	83.82e-6
Rotor resistance referred to stator (ohm)	0.01507
Rotor inductance referred to stator (H)	168e-6
Mutual inductance (H)	6.14e-6
Inertia (kg-m^2)	5.85
Friction factor (N-m-s)	0.05
Pole pairs	1

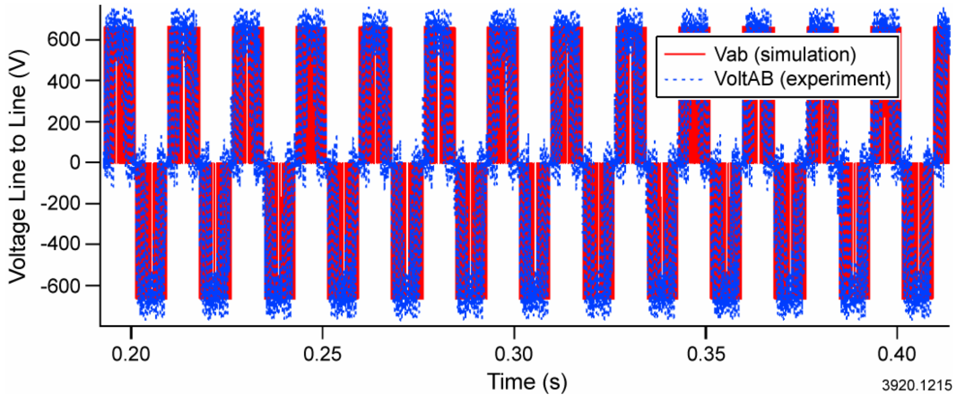

Fig. 2. No-load test – inverter PWM voltage, simulation, and measured values

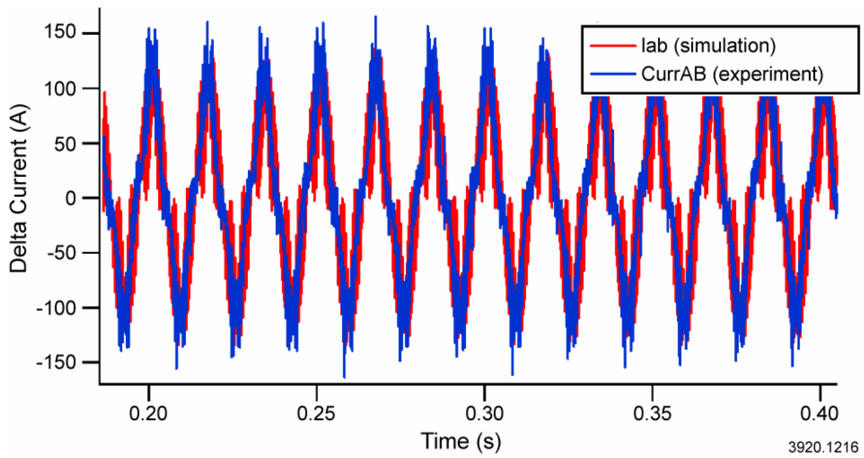

Fig. 3. No-load test – inverter output current, simulation, and measured values

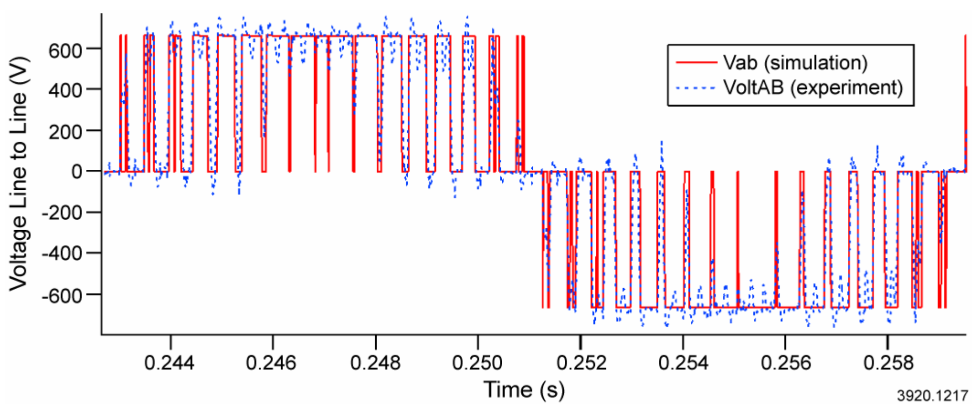

Fig. 4. Expanded view of no-load voltage, simulation and measured values

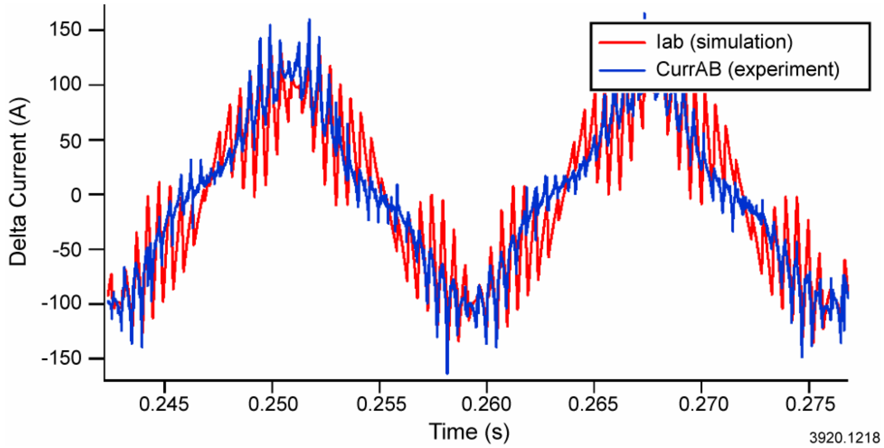

Fig. 5. Expanded view of no-load current, simulation, and measured values

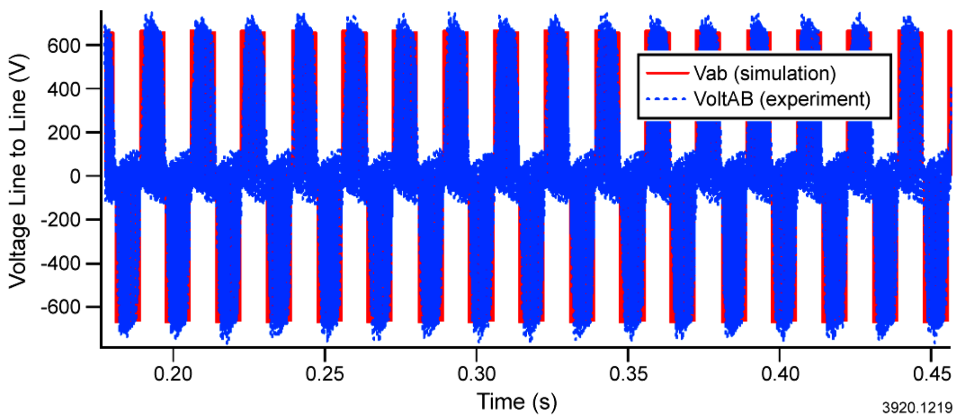

Fig. 6. Locked-rotor test – inverter PWM voltage, simulation, and measured values

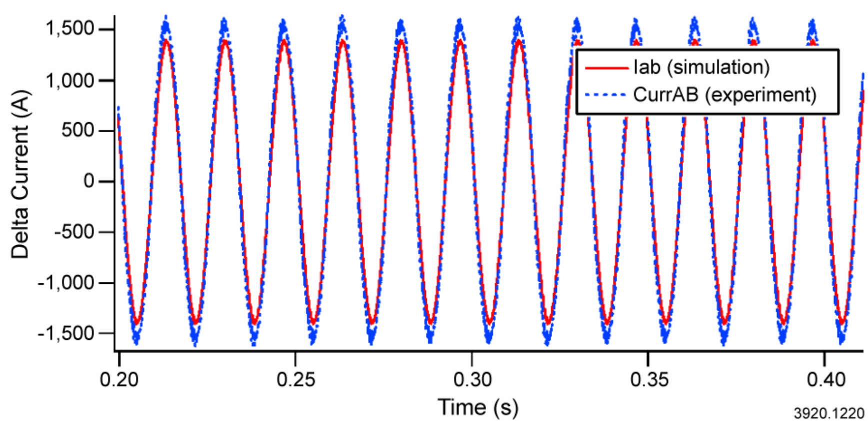

Fig. 7. Locked-rotor test – inverter output current, simulation, and measured values

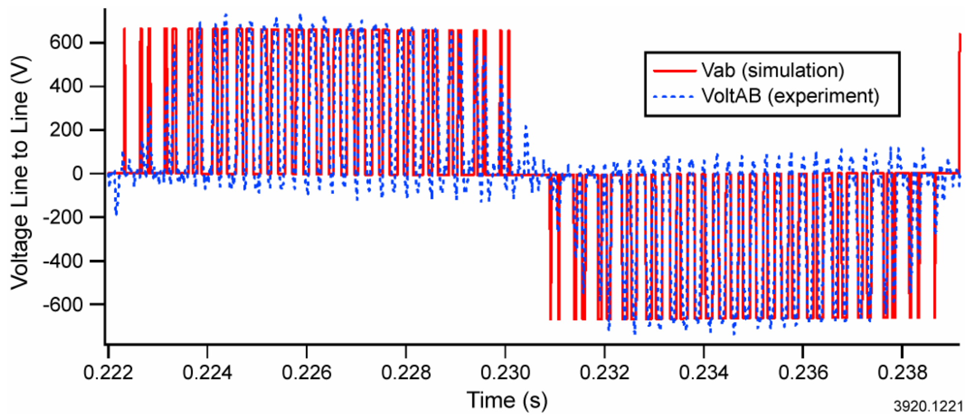

Fig. 8. Expanded view of locked-rotor voltage, simulation, and measured values

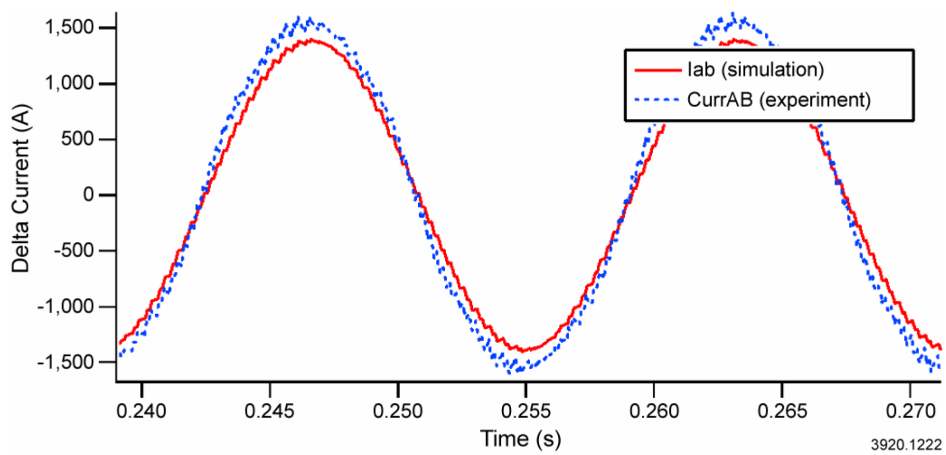

Fig. 9. Expanded view of locked-rotor current, simulation, and measured values

The good comparison of simulation to experimental results gave confidence that this was a good tool for predicting the performance of the prototype motor. In addition, the simulation could be used to accurately predict the harmonics that would be introduced into the motor.

III. INSTRUMENTATION SELECTION

Several iterations were required to arrive at an instrumentation set that would reliably measure the PWM output. Four different voltage probes were used and two current monitors were evaluated. The first voltage probe used was a North Star 500:1 divider. These probes are designed for single-ended compensation, but it can be seen from Fig. 1 that a differential measurement is required to measure the line to line voltage. Next, LEM Instrument Company's voltage monitors were used, but were found to have too narrow a bandwidth to collect the 2 kHz switching frequency of the drive. Tektonix voltage probes were used, but once again the need to compensate the probes differentially proved problematic. The probe could be compensated at one square wave frequency, but it would not hold compensation for a range of frequencies as required to measure the PWM voltage output.

Subsequently, voltages were measured using a voltage divider built by The University of Texas at Austin Center for Electromechanics (UT-CEM) that had been used on high voltage measurements for railgun testing for years. The high voltage leads are connected to two series 1 kΩ resistors and then looped 10 times around a Pearson current transformer. The output is isolated and fairly immune to noise. The problem with this instrument is that the power resistors change their value with heating. The final probe used was a Test Precision Instruments battery operated unit specifically designed for measuring the output of PWM drives. This instrument was found to work well. A similar evaluation was performed for the current measurement. The testing commenced using Pearson current transformers, but they did not provide noise immunity in the PWM environment. From here LEM Instrument Company's current sensors were tested and found to perform well with good noise characteristics. A discussion of the instrumentation is presented in Table 2.

IV. ACCURACY OF MOTOR CHARACTERIZATION USING A PWM

Two complete sets of no-load and locked-rotor tests were run on the Toshiba 500 hp, 3,580 rpm motor using the Magnetek inverter [5] as the power supply. All of the data was taken by transducers interfacing to Nicolet digital oscilloscopes and then downloaded to the computer. The data was computer-analyzed to obtain both the fundamental and rms values of the following parameters.

TABLE 2. INSTRUMENTATION LIST

Instrument	Model	Discussion
VOLTAGE		
North Star 500:1 voltage divider	PVM-10	Not designed to be compensated as differential pair
LEM voltage sensor	#LV100-2000	Not enough bandwidth
Tektronix 1000X high voltage prove	P6015A	Not designed to be compensated as differential pair
UT-CEM voltage divider		Difficult to size power resistor for continuous operation
Test Precision Instruments voltage probe	ADF25A	Performed well, battery maintenance an issue
CURRENT		
Pearson Electronics wide band current transformer pulse current transformer	301X	Noise susceptibility in PWM environment
LEM current sensors	#HAX-2500S	Performed well

- Phase voltage
- Phase current
- Power per phase
- All three phase powers summed to provide the total power

The torque was also measured during the locked-rotor test. The torque signal was averaged to smooth out the instantaneous variations.

This test data was then further analyzed to determine the equivalent circuit parameters and also the locked-rotor and no-load performance. Most of the information obtained from this series of tests can be compared against data on this motor, which was provided by Toshiba. The results are summarized in Table 3.

TABLE 3. SUMMARY OF NO-LOAD AND LOCKED-ROTOR TEST RESULTS

Item	UT-CEM	Toshiba	Error % [a]
R1 (ohms)	0.00337	0.00306	10.1
R2 (ohms)	0.00218 [b]	0.00297	-26.6
$X_1 + X_2$ (ohms)	0.08674 [c]	0.1128	-23.1
X_0 (ohms)	2.31496	3.27	-29.2
Z_{LOCKED} (ohms)	0.08691	0.11296	-23.1
T_{LOCKED} (lb-ft)	1,212.8 [d]	1,319.4	-8.1
I_{LOCKED} (Amperes)	3,689 [d]	3,625	1.7
$I_{NO\text{-}LOAD}$ (Amperes)	114.3	97.0	17.8
$W_{NO\text{-}LOAD}$ (Watts)	6,476		
F & W (Watts)	3,500		
Core loss (Watts)	2,976		

NOTES

a. Based on Toshiba data
b. Measured @ 10 Hz
c. Measured @ 10 Hz and corrected to 60 Hz
d. Measured @ 60 Hz and reduced voltage extrapolated to 460 V

All of the equivalent circuit parameters except for R1 and Xm depend upon the measurements made during the locked-rotor test. The secondary circuit parameters, namely, R2 and X2 are quite frequency-dependent for a motor in the 500 hp size range. This is because of the current crowding effect in the rotor bars, often referred to as deep-bar effect. The Toshiba-provided equivalent circuit parameters are likely the parameters under full-load operating condition where the rotor frequency (slip frequency) is approximately 0.3 Hz.

The inverter will not operate satisfactorily at that low frequency. The first series of tests was run at 60 Hz., which is the usual industrial practice. The tested value of R2 varied from Toshiba's value by 400%. Therefore a second set of tests was run using a

10 Hz frequency for the locked-rotor tests and, as shown in Table 1, the measured value of R2 correlated within 27% against Toshiba's value.

V. Conclusions

- A commercial 500 hp motor was tested using the inverter powered test facility described in both the Part 1 and Part 2 papers. The 500 hp motor was also simulated using Matlab™.
- A comparison of the simulated results and the experimental data for both no-load tests and locked-rotor test has been presented. The results are in very good agreement and inspire confidence in the testing instrumentation and procedures.
- The final instrumentation assembly was the result of several iterations trying different combinations of measurement equipment. The final instrumentation list is presented.

VI. References

1. IEEE Standard Test Procedure for Polyphase Induction Motors and Generators, New York, IEEE Standard 112-1996, The Institute of Electrical and Electronics Engineers, Inc.

2. IEEE Guide: Test Procedures for Synchronous Machines, IEEE Standard 115-1995, New York, The Institute of Electrical and Electronics Engineers, Inc.

3. N. Mohan, T. M. Undeland, and W. P. Robbins, Power Electronics Converters, Applications and Design, John Wiley and Sons, Inc., 1995.

4. P.C. Krause, Analysis of Electric Machinery, McGraw-Hill, 1986.

5. Magentek (now Yaskawa) G5-HHP drive, 575 V class, 1,600 hp.